



Structural Load Alleviation Applied to Next Generation Aircraft and Wind Turbines

Susan Frost, PhD
Intelligent Systems Division
NASA Ames Research Center
Moffett Field, CA



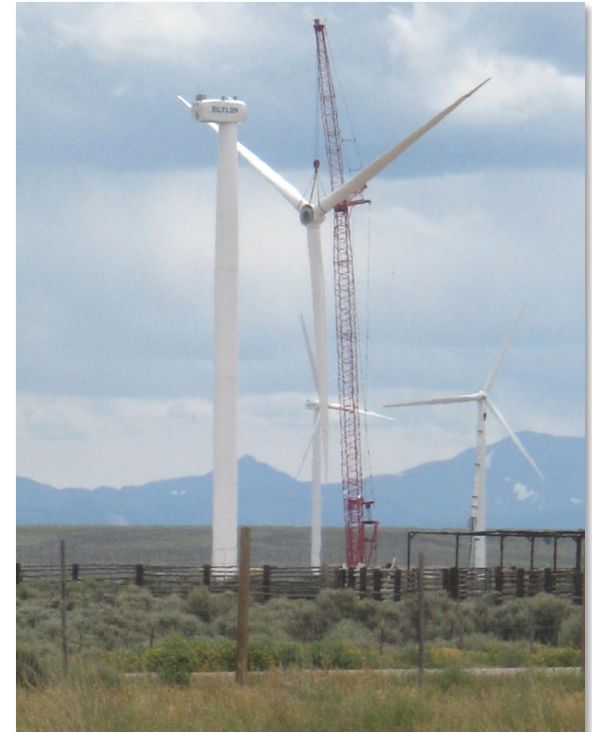
University of Wyoming
Mechanical Engineering Seminar
September 27, 2011

NASA Subsonic Fixed Wing Project, Fundamental Aeronautics Program



Outline

- NASA goals for increased aircraft efficiency
- Proof of concept architecture for flight control with load feedback
- Optimal control allocation with load constraints
- Wind energy challenges
- Wind turbine blade damage
- Adaptive contingency control



SUGAR Ray design by NASA sponsored team led by The Boeing Company



Subsonic Fixed Wing Project

- Reduce environmental impact of aviation
- Increase aircraft efficiency
- Improve mobility of aircraft in airspace

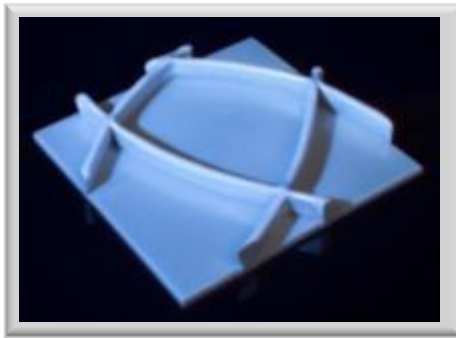
- Unacceptable community noise and other environmental emissions
- Need to reduce fossil fuel consumption
- Demands from NextGen airspace
- Air transportation plays key role in our economy and quality of life

- Create prediction and analysis tools for design
- Develop concepts and technologies for significant improvements in noise, emissions and performance
- Partner with academia, industry, and government



Weight Reduction for Increased Efficiency

- Create new fabrication processes for lightweight materials, esp. large structures
- Design lightweight wing structures with aeroelastic tailoring to eliminate heavy control surfaces
- Use aerogels for super-lightweight insulation
- Increase temperature capability of composites for greater use in engines



Electron Beam Freeform
Fabrication (EBF3)



Polymer-enforced aerogel



Fan containment system with
high temperature capability



Drag Reduction for Increased Efficiency



Formation flight for drag reduction



D-8 (double bubble) has natural laminar flow on wing bottom, design by MIT team

- Increase laminar boundary layer by delaying transition to turbulent flow
 - Design surfaces with favorable pressure gradients (natural laminar flow)
 - Include active or passive local suction surfaces (hybrid laminar flow)
- Use active aeroelastic tailoring of wing to reduce drag during cruise
- Advanced CONOPS – formation flight
- Develop & validate CFD codes for design & analysis of advanced drag reduction concepts

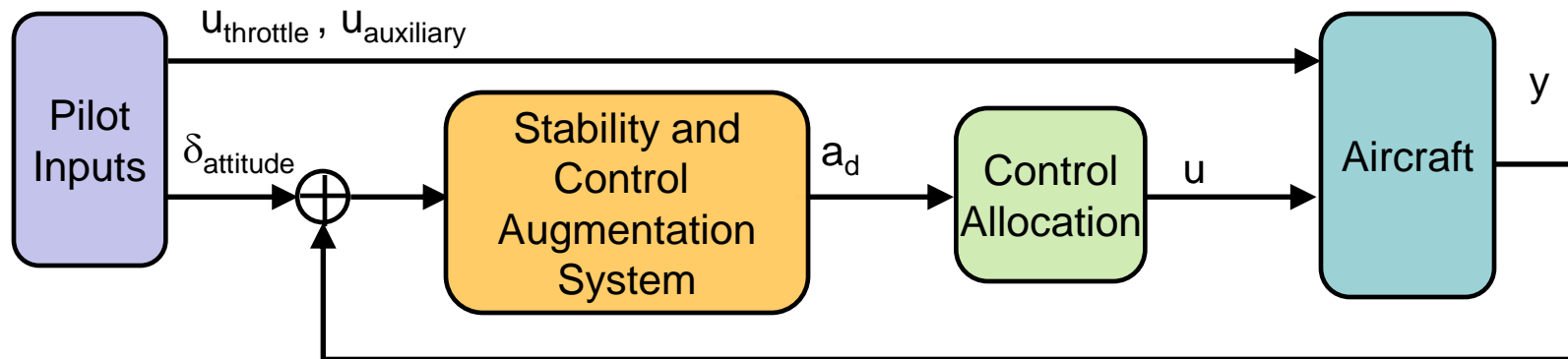


NextGen N+3 Concept Aircraft





Traditional Flight Control System



Control Allocation: Determine surface deflections needed to achieve desired rates

➤ Traditional Approaches for Control Allocation

- **Ganging of Actuators:** use elevator for pitch, ailerons for roll, rudder for yaw
- **Mixers:** fixed combination of surfaces to achieve commands

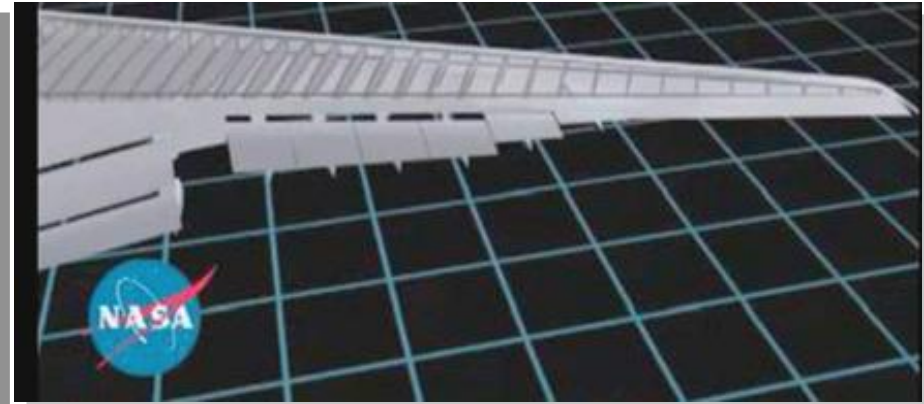
➤ Structural Limits

- Design engineers determine critical load paths in aircraft
- Mostly concerned with bending, torsion, and shear loads
- Load limits are determined through ground tests and flight tests
- Load limits imposed by restricting flight envelope; position & rate limiting actuators



New Challenges for Flight Control Systems

- Many redundant effectors
- Surfaces affecting multiple axes
- Actuator rate & position saturation
- Low control authority
- Lighter more flexible structures



Optimal Control Allocation

Given \mathbf{B} , a desired vector \mathbf{u}_p and $\varepsilon > 0$, find \mathbf{u} such that

$$J = \underbrace{\|\mathbf{B}\mathbf{u} - \mathbf{a}_d\|}_{\text{error minimization}} + \varepsilon \underbrace{\|\mathbf{u} - \mathbf{u}_p\|}_{\text{control minimization}}$$

No Structural Constraints!!

is minimized subject to $\mathbf{u}_{\min} \leq \mathbf{u} \leq \mathbf{u}_{\max}$, $|\dot{\mathbf{u}}| \leq \dot{\mathbf{u}}_{\max}$



Objective:

Use multiple control surfaces in most effective way, while remaining within structural load limits

Approach:

Replace traditional control allocation with optimal control allocation with load constraints and real-time load feedback

- Measure internal (structural) loads along critical load paths
- Use aircraft aerodynamic and structural models to determine incremental loads due to incremental surface deflection
- Include structural load constraints and measured loads in optimal control allocation problem

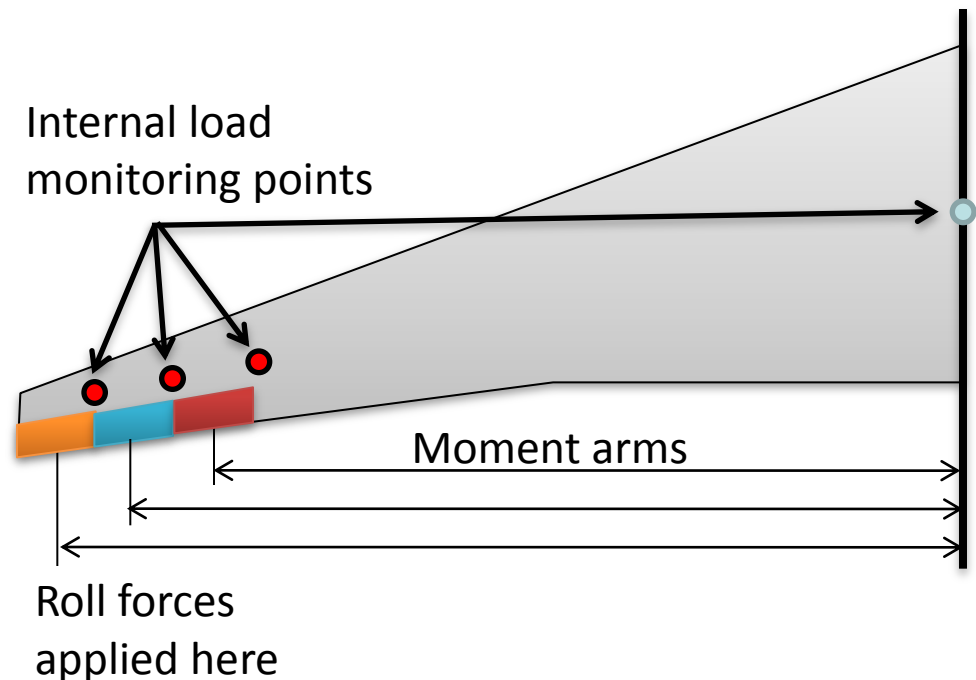
Significance:

This approach enables fuel efficient aircraft with many multi-purpose control surfaces to achieve acceptable performance & safety



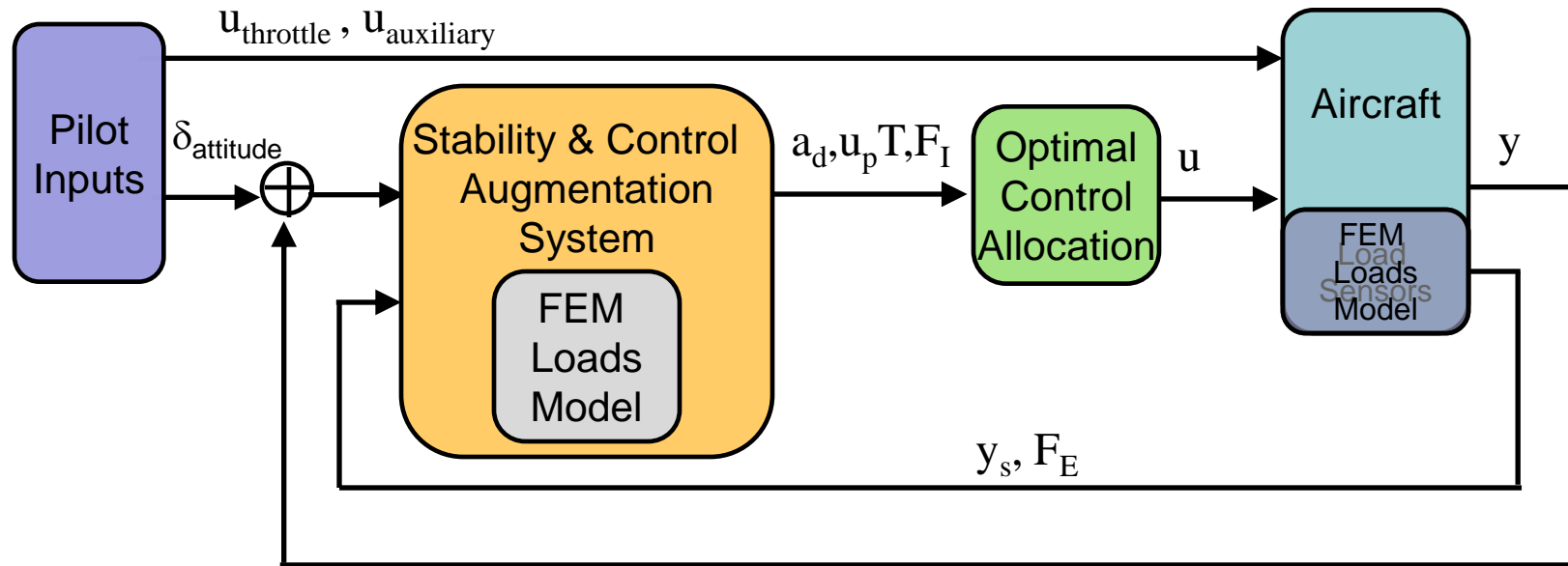
Study Assumptions

- Only considering static loads due to lift and rolling forces
- Finite element model (FEM) of aircraft wings and tail
- Loads due to lift and roll are applied to nodes in FEM model
- Bending moments calculated using finite element analysis (FEA)
- A select number of load points are monitored and included in the optimal control allocation constraints





Proposed Framework



a_d	desired accelerations
u_p	preferred delta surface positions
B	control effectiveness matrix
T	incremental loads matrix, where Tu gives the incremental loads at critical points
y_s	structural loads from sensors (or model in sim)
F_E	external forces due to lift and body moments
F_I	internal structural loads at critical points



Optimal Control Allocation

Optimal Control Allocation Problem:

Given B , a desired vector u_d and $\varepsilon > 0$, find u such that

$$J = \underbrace{\|Bu - a_d\|_1}_{\text{error min}} + \varepsilon \underbrace{\|u - u_d\|_\infty}_{\text{control min}}$$

is minimized subject to:

$$u_{\min} \leq u \leq u_{\max}, \quad F_I + Tu \leq F_{I,\max}$$

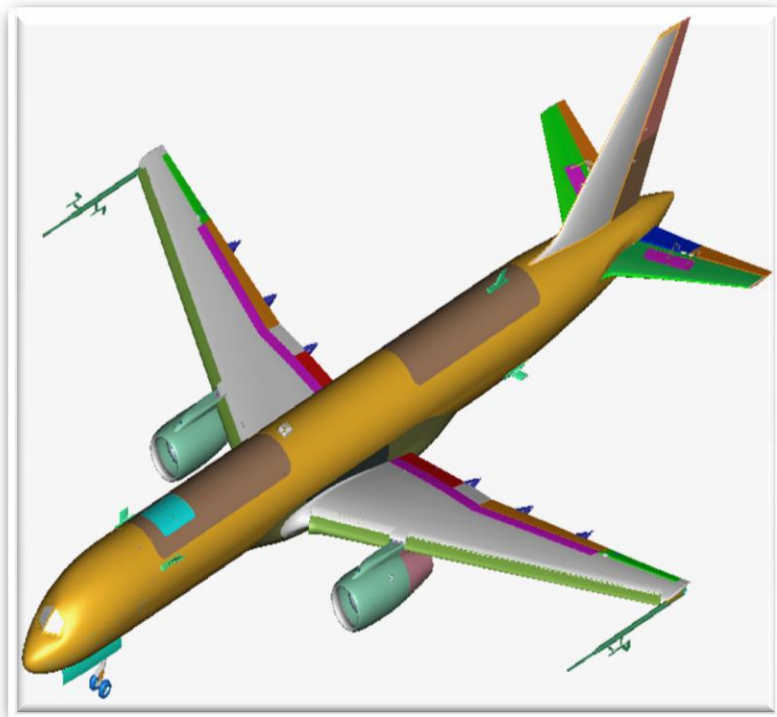
where $F_{I,\max}$ are critical point load limits

Can also be formulated with load minimization, using constraints given above and cost function:

$$J = \|Bu - a_d\| + \varepsilon \|u - u_d\| + \underbrace{\gamma \|F_{I,\max} - F_I + T(u - u_p)\|}_{\text{load min}}$$



Up-scale GTM Simulation



5.5% GTM-T2 Solid Model

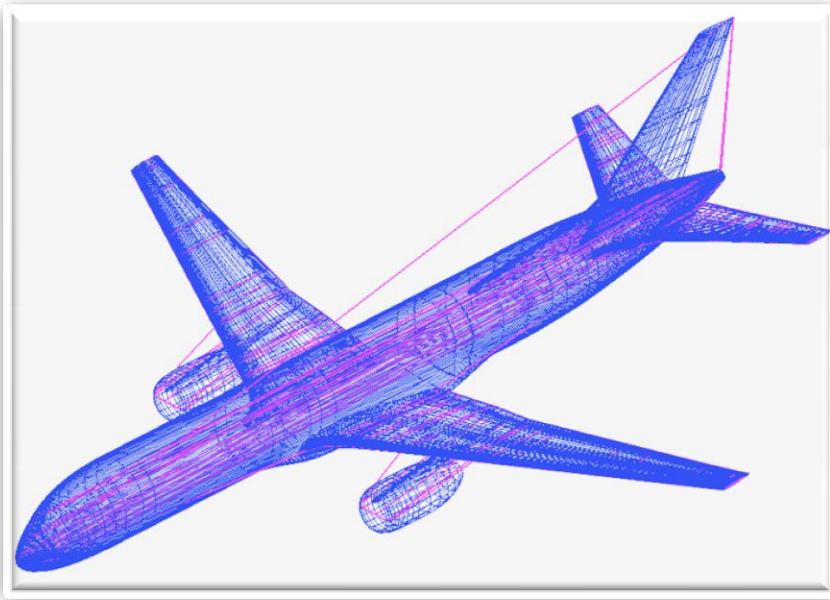
Up-scale GTM Simulation

- Simulink model based on 5.5% dynamically scaled aircraft derived from wind tunnel & flight test data
- Up-scaled by incorporating Reynolds adjusted aero tables
- Actuator models sized for up-scale GTM
- NASA Glenn's Simp2 engine (simplified version of C-MAPSS40k)
- GTM bare airframe
- 6 ailerons, 4 elevons, 2 rudders, 2 stabs, 2 flaps
- Vehicle Management System
 - sensor processing module
 - mission manager
 - guidance/control
- Vehicle Control Augmentation System
 - reference model dynamic inverse controller
 - optimal control allocator

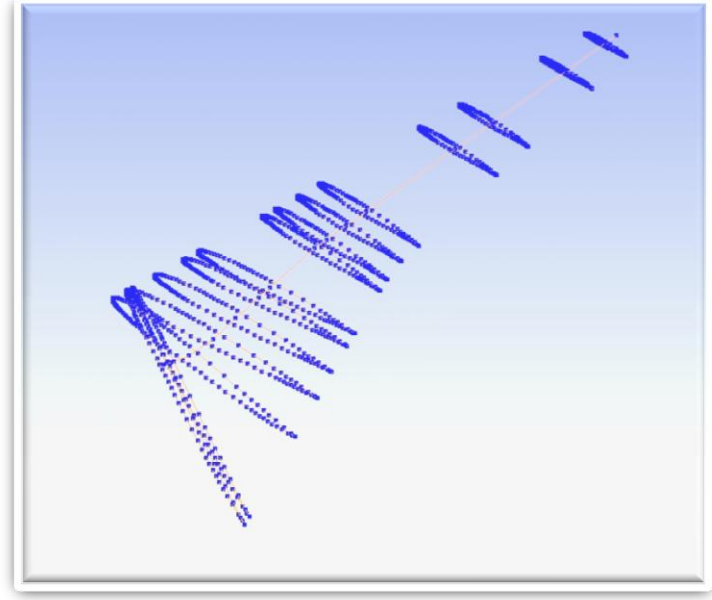


Finite Element Modeling Approach

- Wings/tails modeled as cantilever beams with fixed ends at roots
- Constant thickness hollow aluminum shells following outer mold line give beam cross section properties
- Beam nodes located at centroids of wing cross sections



Vortex-lattice model of aircraft

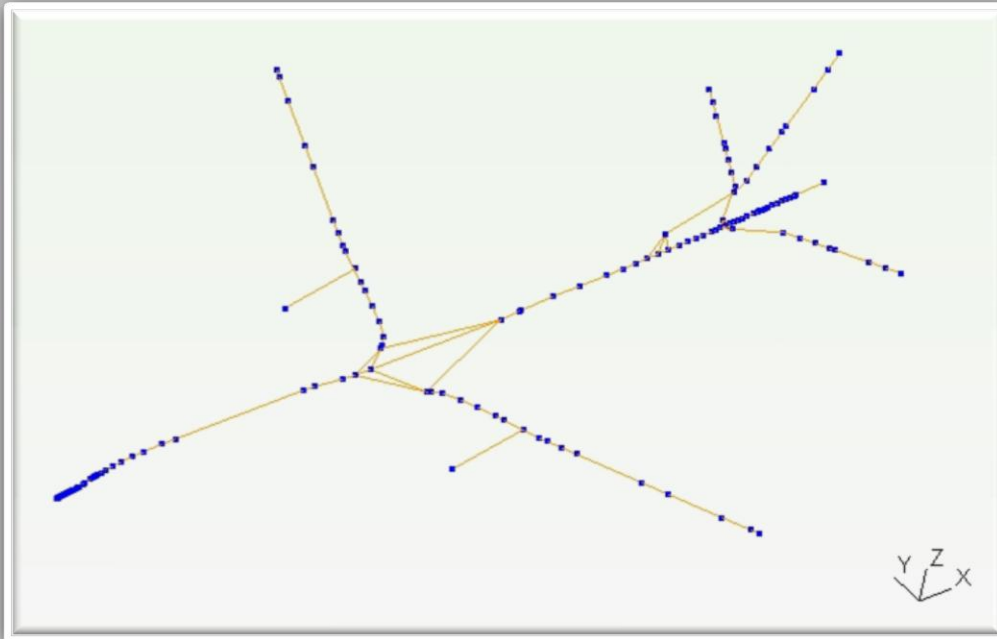


Wing cross sections

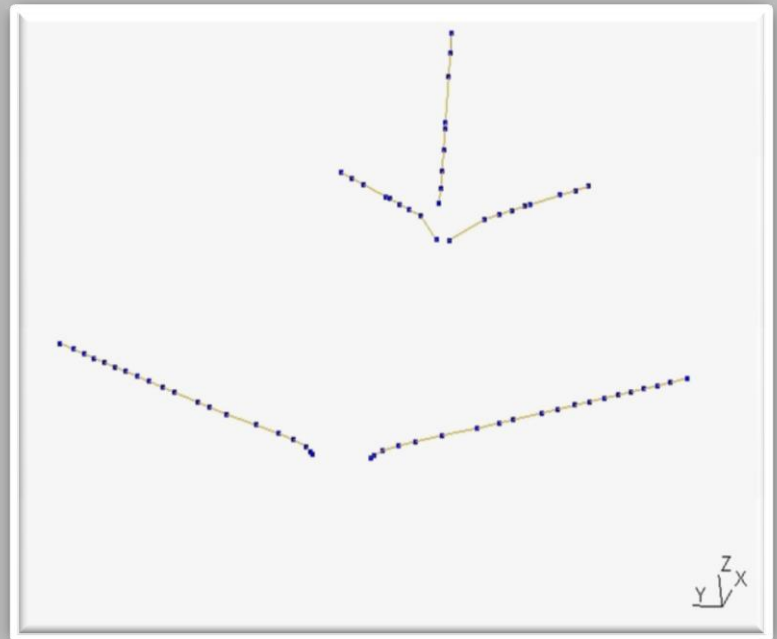


Finite Element Model of GTM

- Beam mesh for each wing has 20 nodes and 19 beams
- Each beam has 6 degrees of freedom – 3 translation & 3 rotation



FEM of GTM aircraft

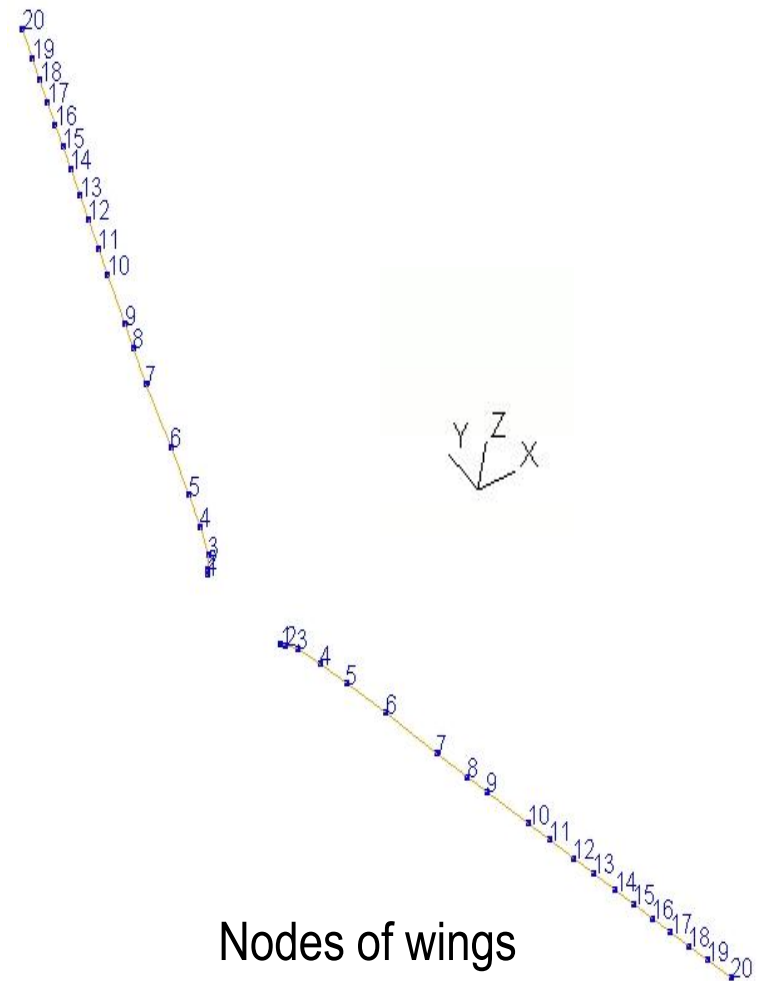


FEM of wings and empennage



Finite Element Analysis

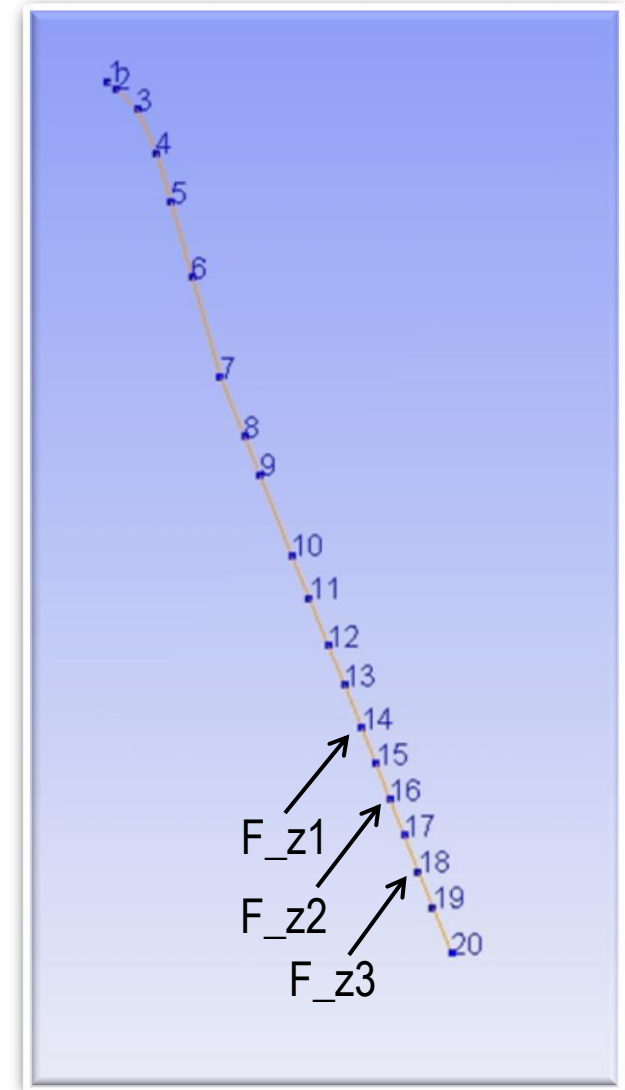
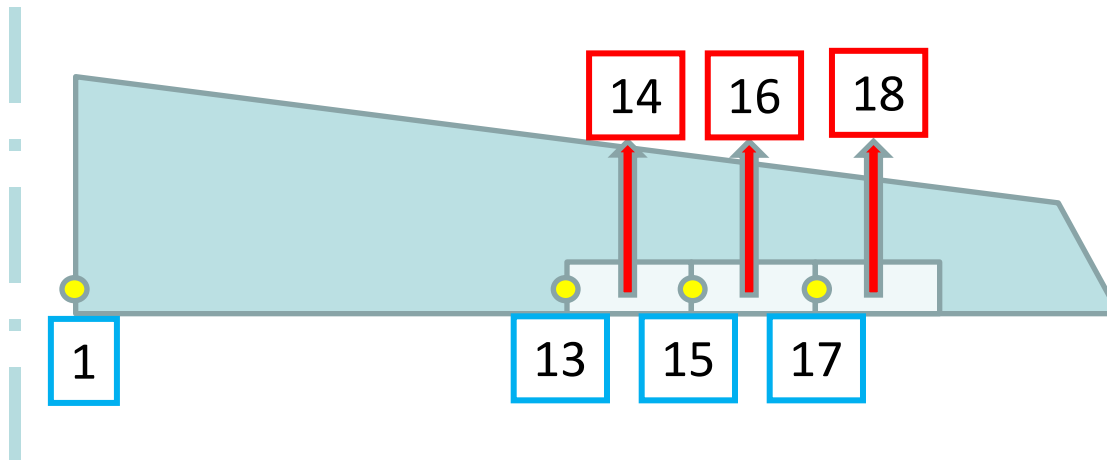
- Assume static loads and static response, $F = Kx$
- Stiffness matrix \mathbf{K} is derived from FEM
- \mathbf{K}^{-1} is computed off-line
- Static loads applied during simulation to FEA nodes
- Measured loads are calculated from deflections using \mathbf{K}^{-1}





Application of External Static Loads

- Elliptically distributed lift load applied to nodes along wings and horizontal tail
- Loads arising from roll moments applied as concentrated forces in z-direction on each aileron in proportion to aileron deflection

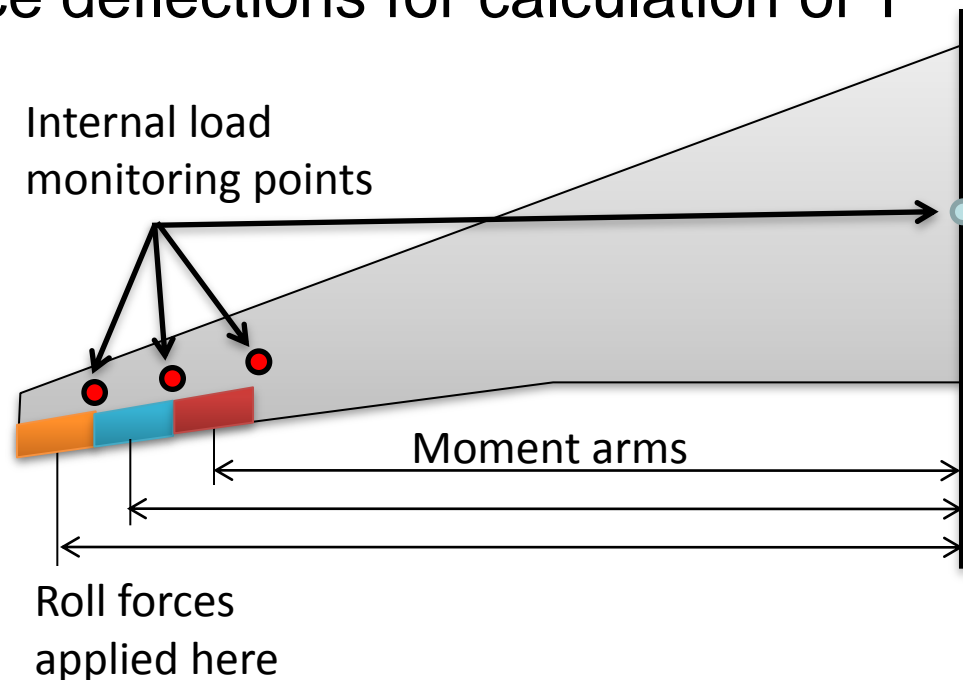


Roll force locations



Integration with Simulation

- Flap-wise bending moment at critical points are calculated & passed to control allocator
- K^{-1} and B are used during simulation to determine incremental loads matrix T
- Aileron forces are assumed to be proportional to surface deflections for calculation of T





Flight conditions:

- Altitude 30,000 ft
- Mach 0.85

Test cases:

- **Normal case**
Load limits set to values determined for safe flight
- **Case I**
Right aileron load limit set to 55,000 ft-lb
- **Case II**
Left outboard aileron deflection limits set to ± 0.01 deg

Example of control allocation gone bad

COMMANDED ROLL MANEUVER

Both produce same roll moment

Surface deflection (d)

Structural load limits exceeded



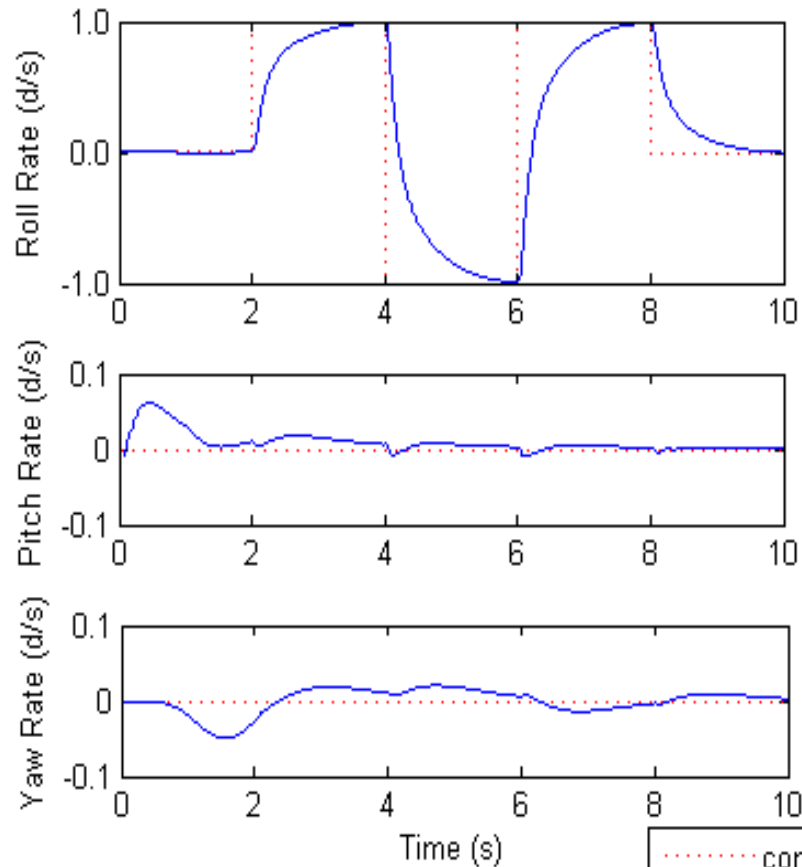
Structural loads within limits



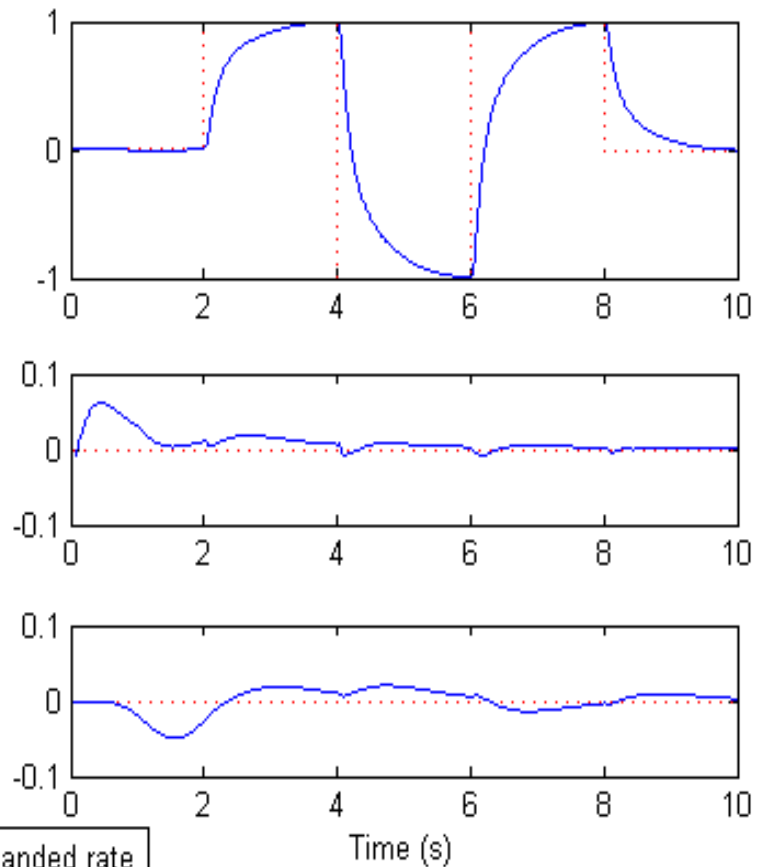


Roll Doublet Case I

Normal Load Constraints



Reduced Load Constraints

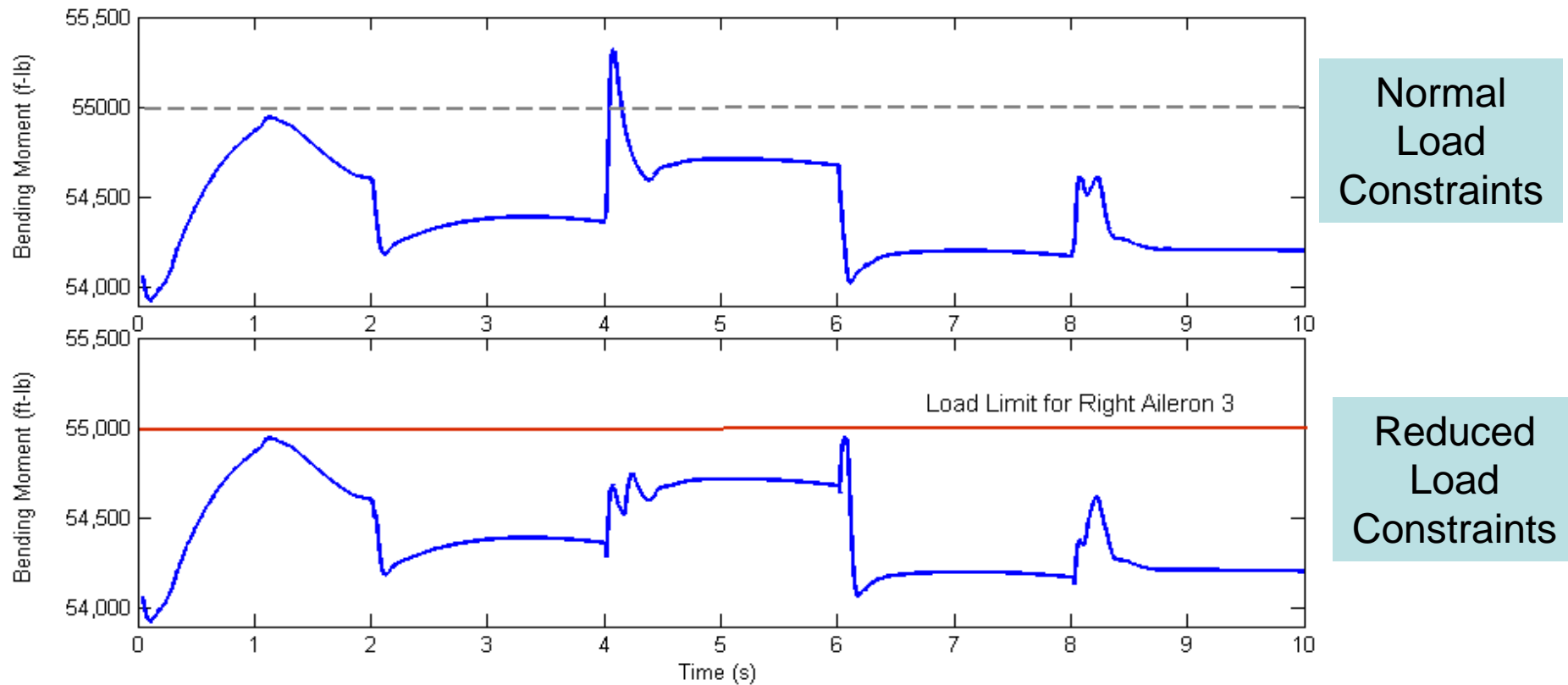


..... commanded rate
— sensed rate



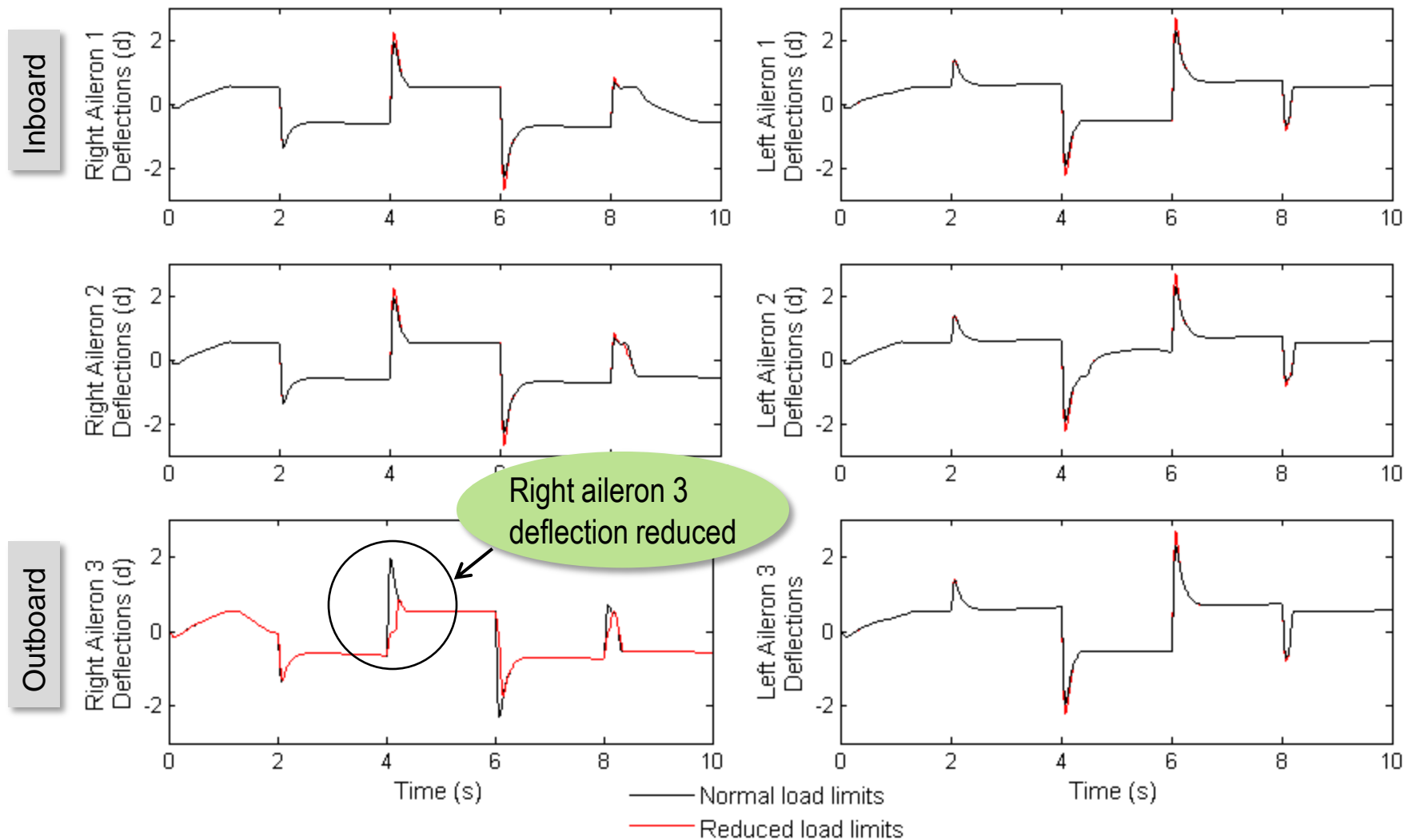
Bending Moment for Right Outboard Aileron

Case I: Outboard aileron critical point limit set to 55,000 ft-lb





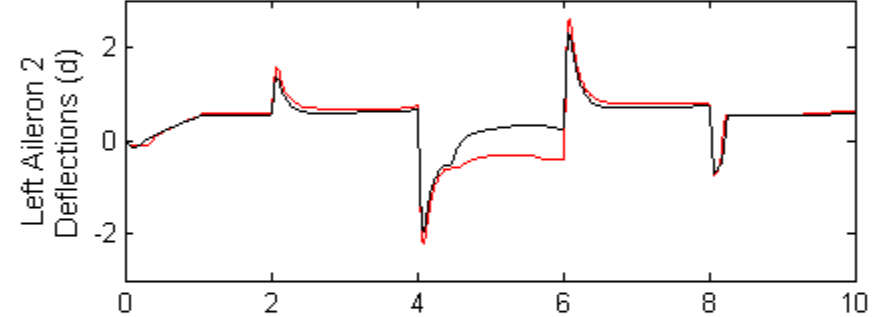
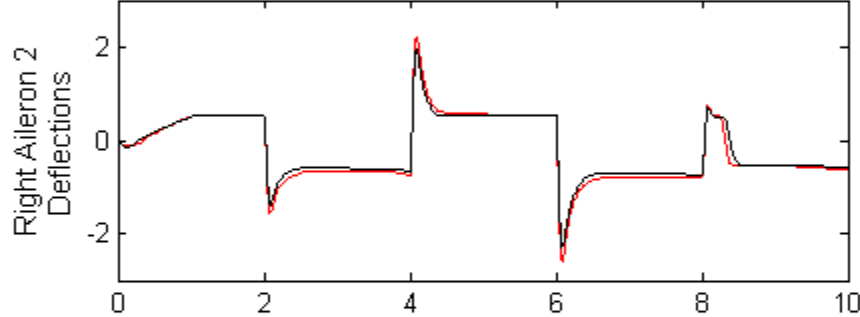
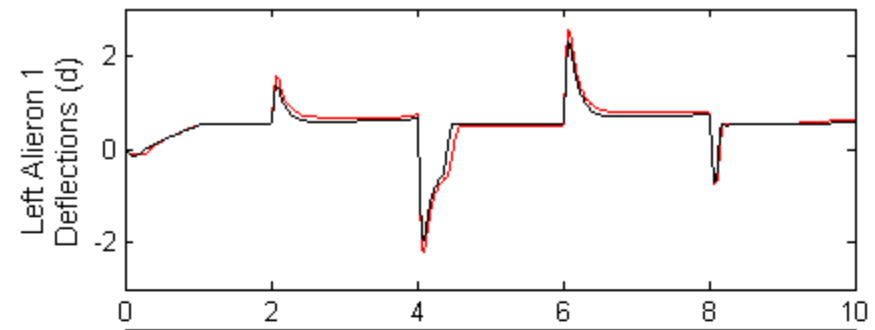
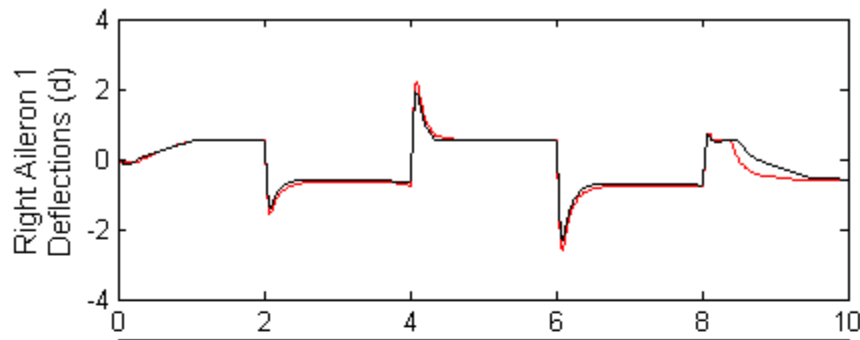
Aileron Deflections Case 1



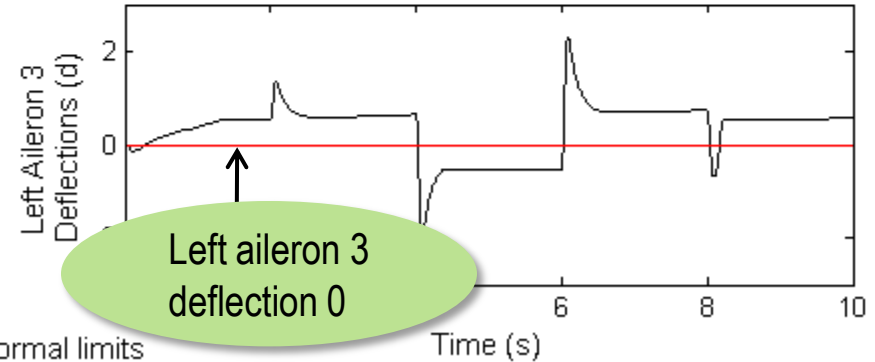
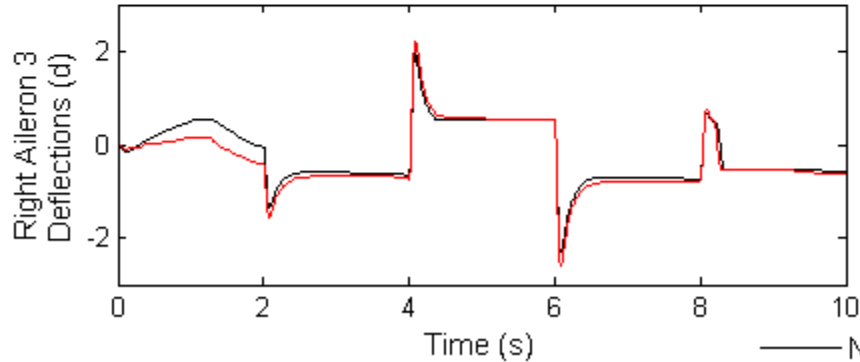


Aileron Deflections Case II

Inboard



Outboard



— Normal limits
— Restricted position limit



Formulation & Solution Approaches

Mixed Optimization Formulation

Find u that minimizes $J = \|(CB)u - a_d\| + \varepsilon \|u - u_p\|$

subject to $u_{\min} \leq u \leq u_{\max}, |\dot{u}| \leq \dot{u}_{\max}$

Solution Approaches Using Different Norms

❖ **ℓ_1 norm:** $\|u\|_1 \equiv \sum_i |u_i|$

Convert to linear programming problem

- Simplex algorithms (Bodson)
- Interior-point algorithms (Peterson, Bodson)

❖ **ℓ_2 norm:** $\|u\|_2 \equiv \sqrt{\sum_i u_i^2}$

- Active Set Method with norms squared (Härkegård)
- Interior-point algorithms

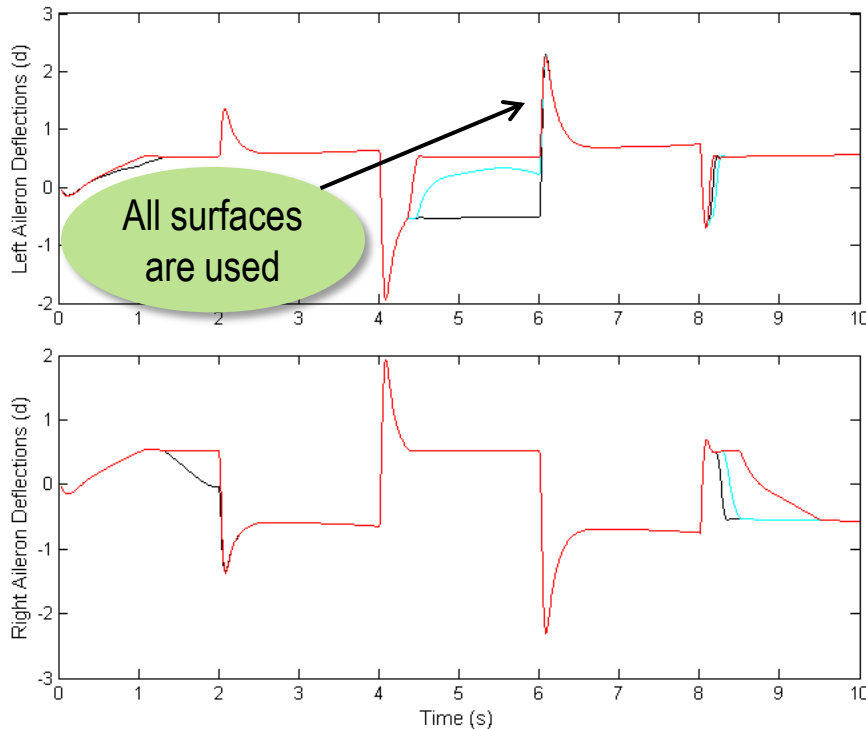
❖ **ℓ_∞ norm:** $\|u\|_\infty \equiv \max_i (u_i)$

- Simplex algorithm (Bodson, Frost)

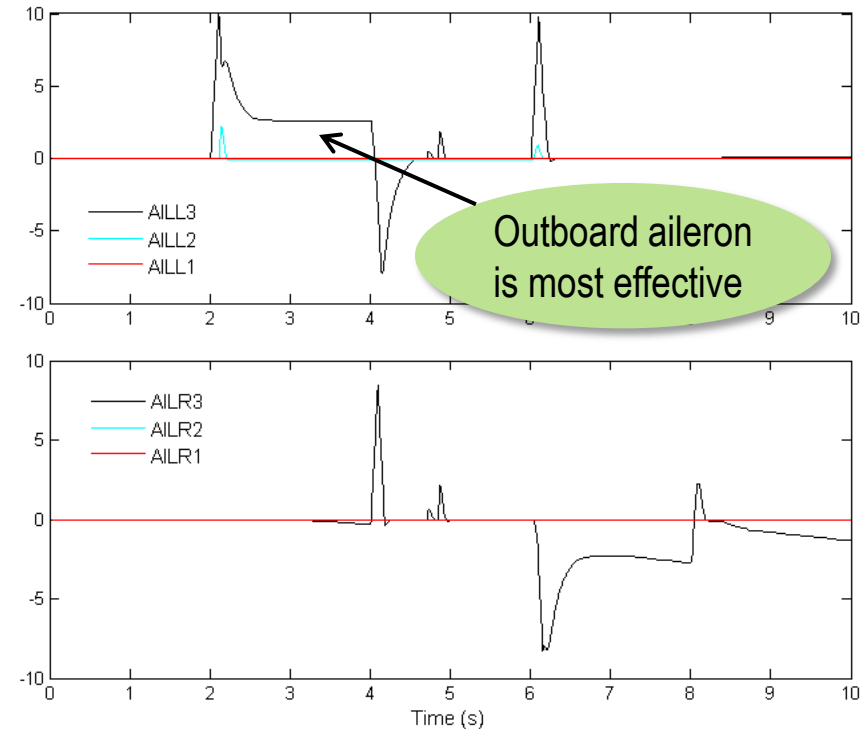


Normal Case with l_∞ versus l_1 Norm on Control

l_∞ Norm on Control

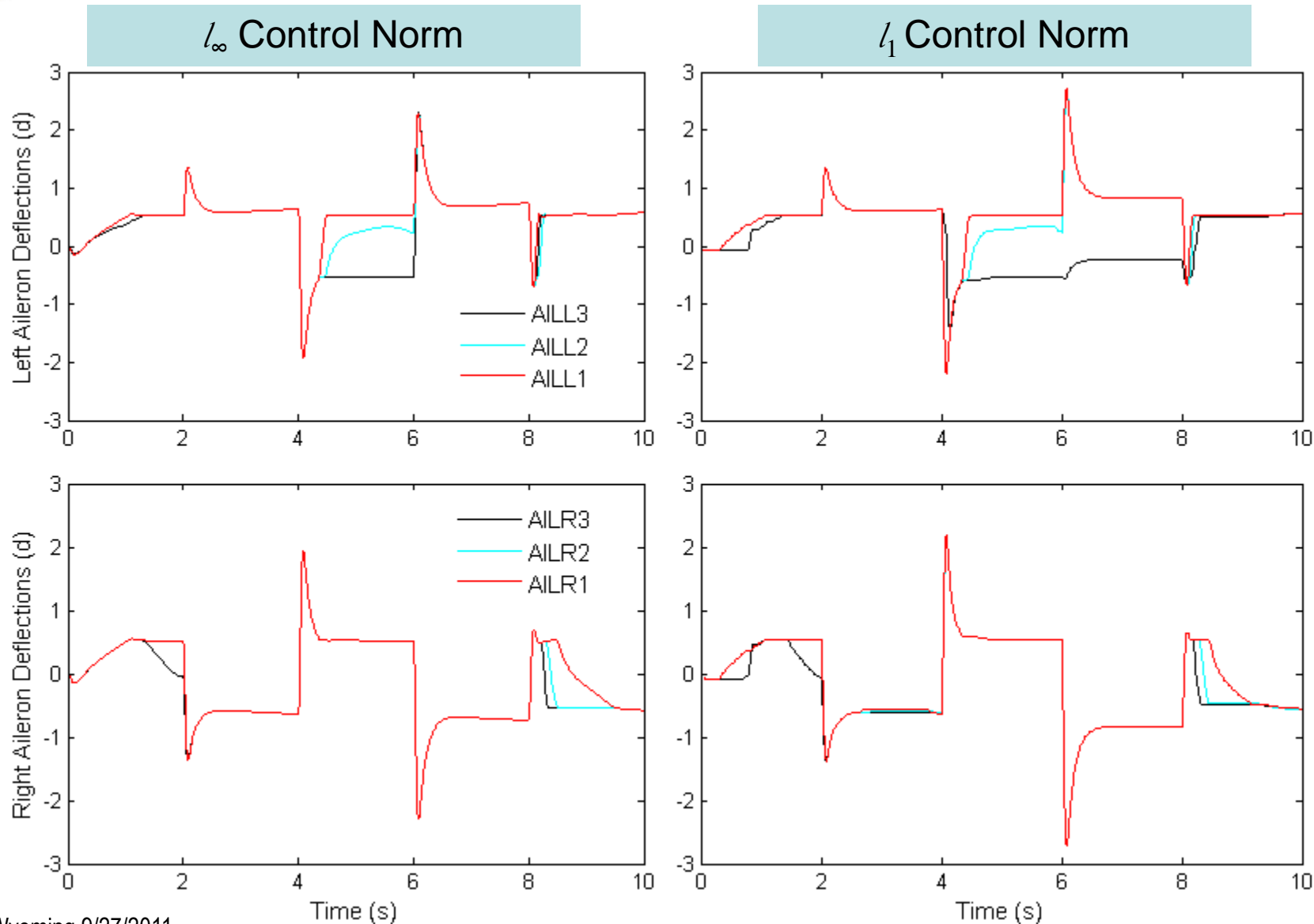


l_1 Norm on Control





Normal Case with l_∞ versus l_1 Control Norm





Conclusions & Future Work

Proposed framework performed adequately in simulation & proof of concept demonstration was successful

- Control allocation
 - Try load minimization
 - Use weights on surfaces and critical points depending on health of components
 - Explore non-feasible solutions
- Loads model
 - Investigate robustness, computation time, sensitivity
 - Include torsion, structural dynamics
- Work with sensors to measure loads
- Include aeroelasticity in simulation
- Flight test technology at Dryden Flight Research Center



Our Next Challenge: Distributed Control Effectors

Objective:

- Develop variable stiffness materials for distributed control effector skins

Approach:

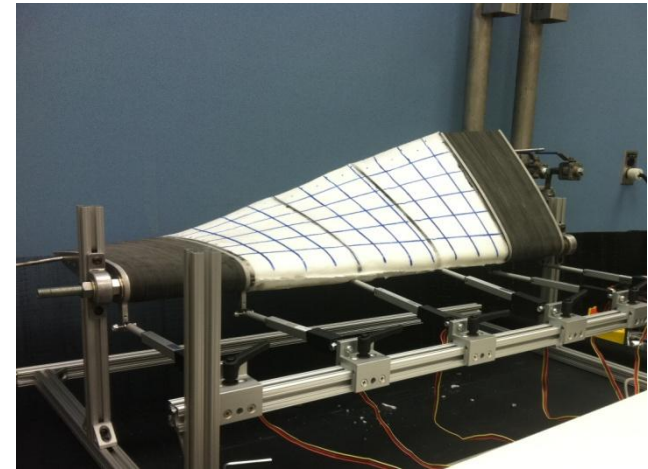
- Investigate mechanisms that can impart variable stiffness to material systems to enable novel control effectors to control lightweight flexible wings
- Test various concepts on distributed control effector model to determine feasibility as a structural element

Significance:

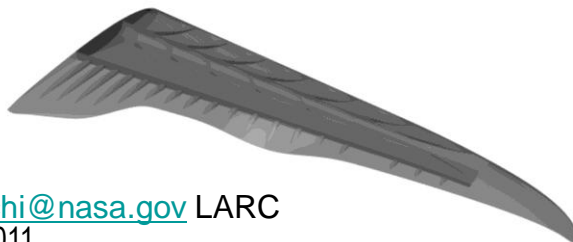
- Variable stiffness material systems can enable control of aeroelastically tailored lightweight wings to meet SFW fuel burn goals

Results:

- Bench model (shown top right) developed to study angles and deformations of distributed control effectors to develop requirements and test candidate variable flexibility control surface skins
- This activity will involve materials, structures, aeroelastics, controls and dynamics experts working concurrently to design, analyze, build and test a distributed control surface concept



Above: Bench model of distributed control surface
Below: Sketch of aeroelastically tailored wing with distributed control effector on trailing edge





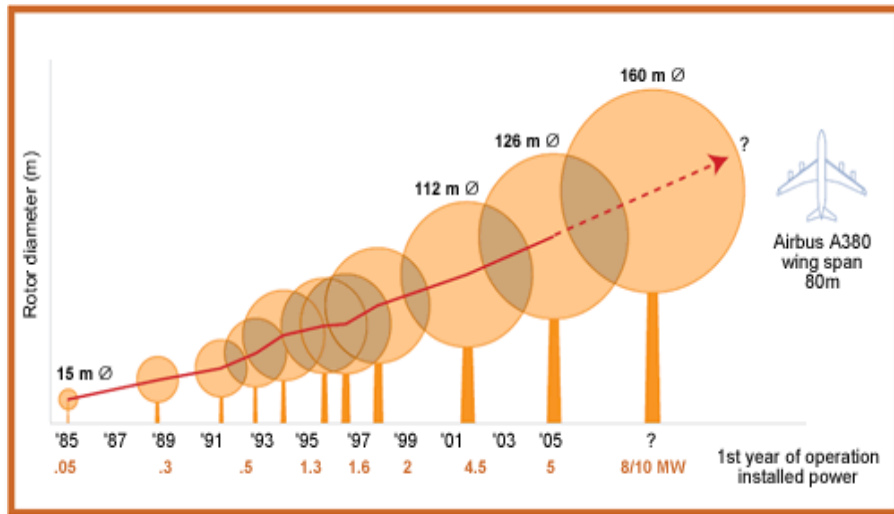
Wind Industry Observations

Wind Industry Practices

- Industry is relatively low-tech and very protective of IP
- Research funding is limited
- Very little vertical stratification
- New technologies need **quick** and **cost-effective** integration

Wind Industry Challenges

- Building large turbines (>5 MW)
- Operating & maintenance costs
- Turbine reliability
- Grid integration
- Community noise
- Wind farm siting





Condition Monitoring in Wind Turbines

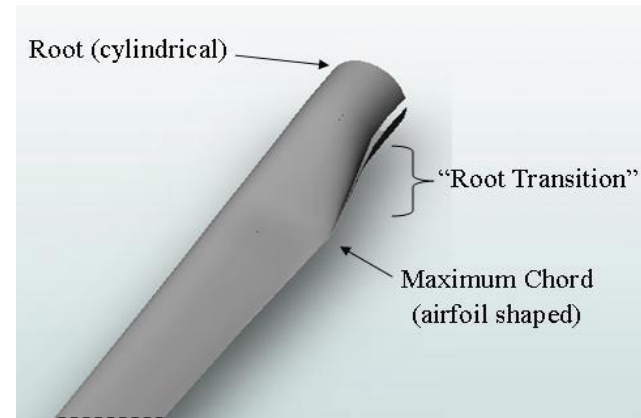
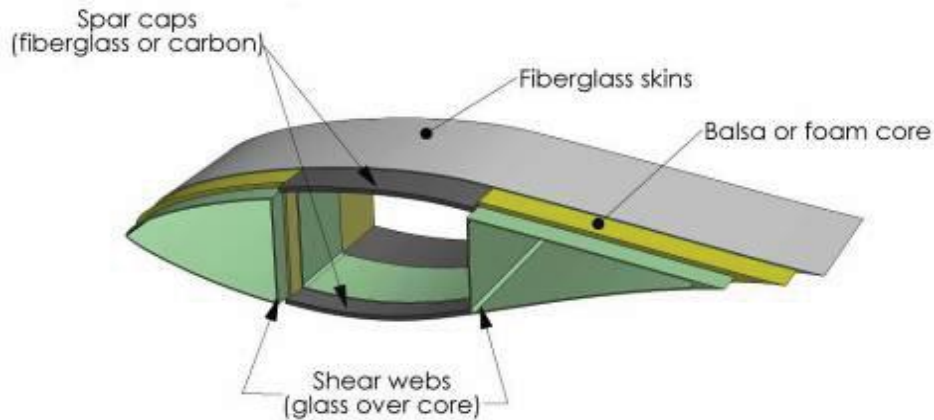
- SCADA system
 - Supervisory Control and Data Acquisition for wind farm
 - Medium- and long-term changes in environmental & operating conditions
 - Minimal fault diagnosis
 - Lots of data, not always useful
- Short-term condition monitoring
 - Equipment set up for one month for vibration, acoustic, strain, nacelle acceleration testing
- Scheduled maintenance & inspection
- Acceptance of CM by operators/developers
 - Dependent on cost of CM system
 - Might affect warranty
- Some OEMs are moving towards guaranteed uptime



Image: www.vertigo.net.au



Leading Causes of Blade Failures¹



- 1) Manufacturing defects - wrinkles in laminate, missing or incomplete bond lines, dry fibers
- 2) Progressive damage initiating from leading-edge erosion, skin cracks, transport, handling, or lightning strikes
- 3) Excessive loads from turbine system dynamics or dynamic interaction with control system
- 4) Out-of-plane forces and distortion of blade sections ("bulging/breathing" effect) mostly in root transition region, due to blade loading
- 5) Excessive loads due to unusually severe atmospheric conditions

¹DNV Renewables, Seattle, WA, "Lessons Learned from Recent Blade Failures: Primary Causes and Risk-Reducing Technologies", D.A. Griffin & M.C. Malkin, 49th AIAA Aerospace Sciences Meeting, Jan 2011, paper no. 2011-259



Flexible Structure Control

Flexible Structure Control Challenge:

- Structural modes can be excited by feedback control
 - Low pass filter can reduce problems, but they have limitations
 - Residual mode filter (RMF) has model of structural mode, including phase and frequency, that can be removed from feedback
 - Flexible structures ARE intrinsically modal systems
-
- Flexible aerospace structures are difficult to model and they operate in poorly known environments
 - Adaptive control **helps**, but requires minimum phase plants (ASPR)
 - Residual Mode Filters (RMF) can cancel transmission zeros, restoring ASPR

Recall: A system (A, B, C) is ASPR when $CB > 0$ and its closed-loop transferfunction $P(s) = C(sI - A)^{-1}B$ is minimum phase.



Partition Plant into ASPR & non-ASPR

Assume original system $(\mathbf{A}_p, \mathbf{B}_p, \mathbf{C}_p)$ can be partitioned into:

$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{x}_Q \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix} + \begin{bmatrix} B \\ B_Q \end{bmatrix} u_p + \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix} u_D \\ y_p = \begin{bmatrix} C & C_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix}; \quad \varepsilon \geq 0 \end{cases}$$

Use RMF to remove these modes from controller feedback

Controlled Plant

Reduced Order Model

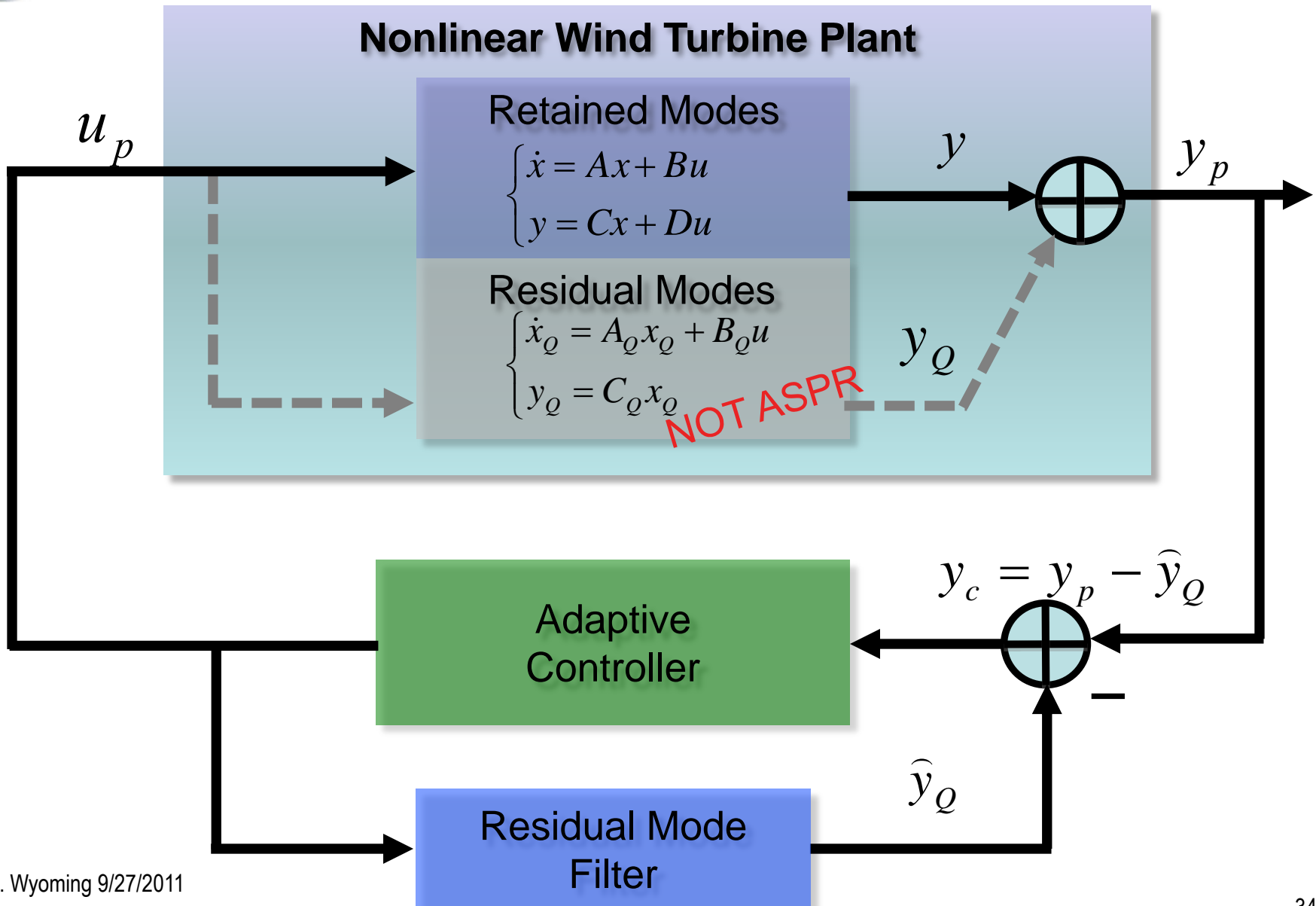
All Open-Loop
Unstable Modes
that are ASPR

All Residual Modes

Q modes
Open-loop stable
not ASPR
in Closed-Loop



Adaptive Controller using RMF





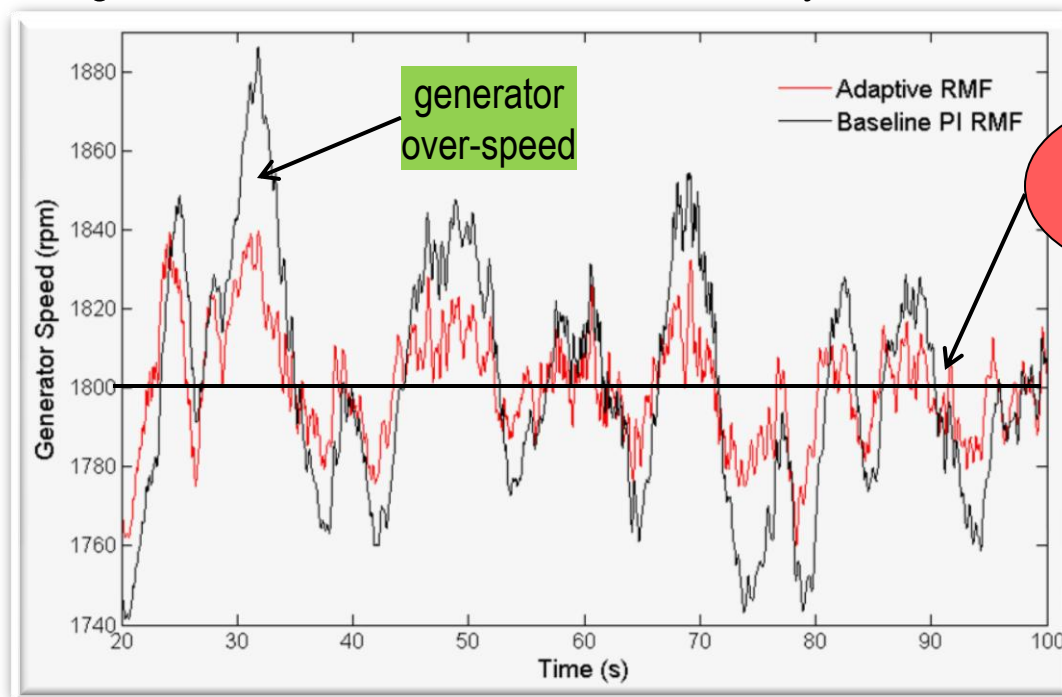
Adaptive Pitch Control for FAST Simulator*

- **Objective:** Regulate generator speed and reject disturbances
- **Input:** Rotor speed
- **Output:** Collective blade pitch, constant generator torque
- **Disturbance:** Step function
- **How:** Model gusts as step functions
- **RMF** Designed for drive-train rotational flexibility mode

Generator speed for
turbulent wind input

---- Baseline PI

---- Adaptive RMF





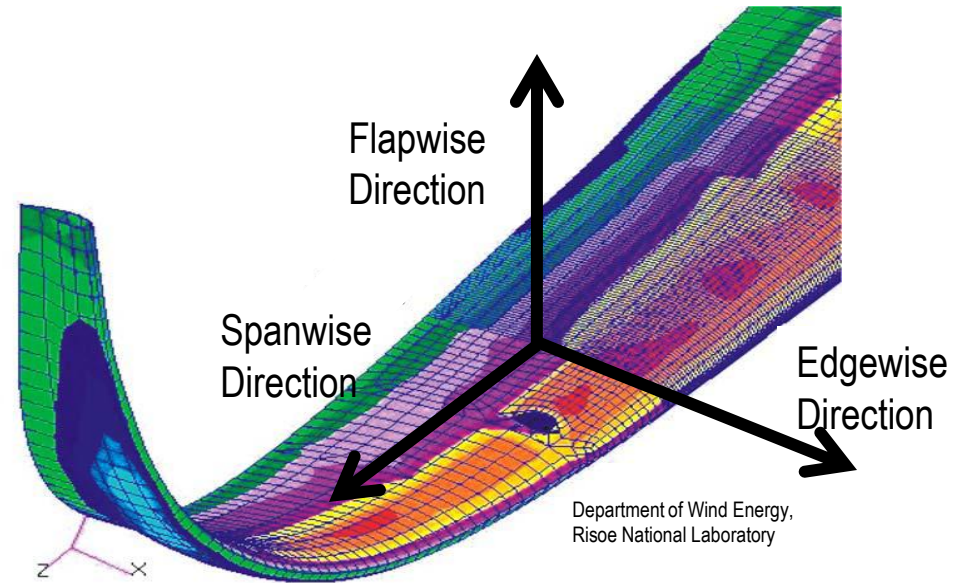
FAST Turbine Blades

FAST blade configuration files:

- 21 distributed stations along span
- Flapwise & edgewise stiffness
- Flapwise & edgewise bending modes

Assumption:

Blade damage can be represented by reduction in flapwise & edgewise stiffness



Damaged blade configuration files:

- Edgewise and flapwise stiffness are varied at a blade station
- Blade bending mode shapes are recomputed
- Structural damping and other parameters were left unchanged

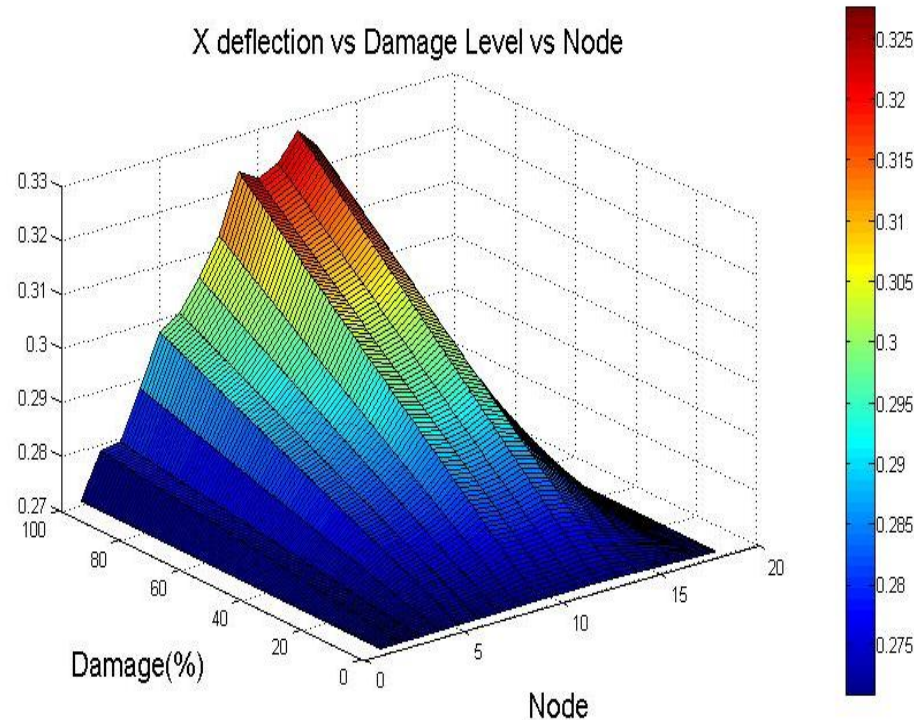


Blade Node Sensitivity to Stiffness Changes

Full factorial study performed to determine node sensitivity:

- Parameters: blade damage, wind speed, blade pitch
- Levels: 8 for damage, 7 for wind, 10 for blade pitch

Loads on blades are primarily due to aerodynamic forces





Study of Turbine Response to Blade Damage

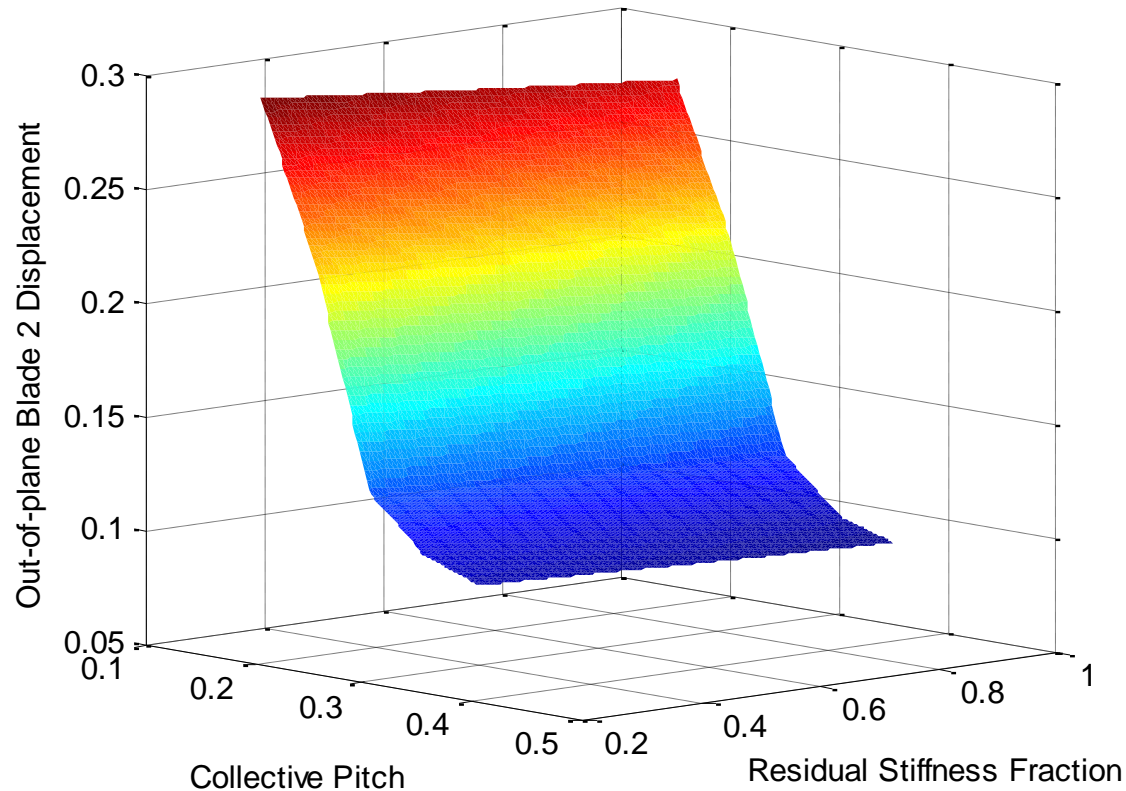
Preliminary study of effects of blade stiffness reduction

- Damage located on one blade at station 7, 30% from blade root
- Study run in open-loop with no generator speed tracking
- Generator torque held fixed at rated torque
- Simulation run with steady wind speeds from 12-24 mps
- Collective pitch varied from 0.1-0.45 radians
- Blade tip displacement was measured





Tip Displacement vs Pitch vs Damage

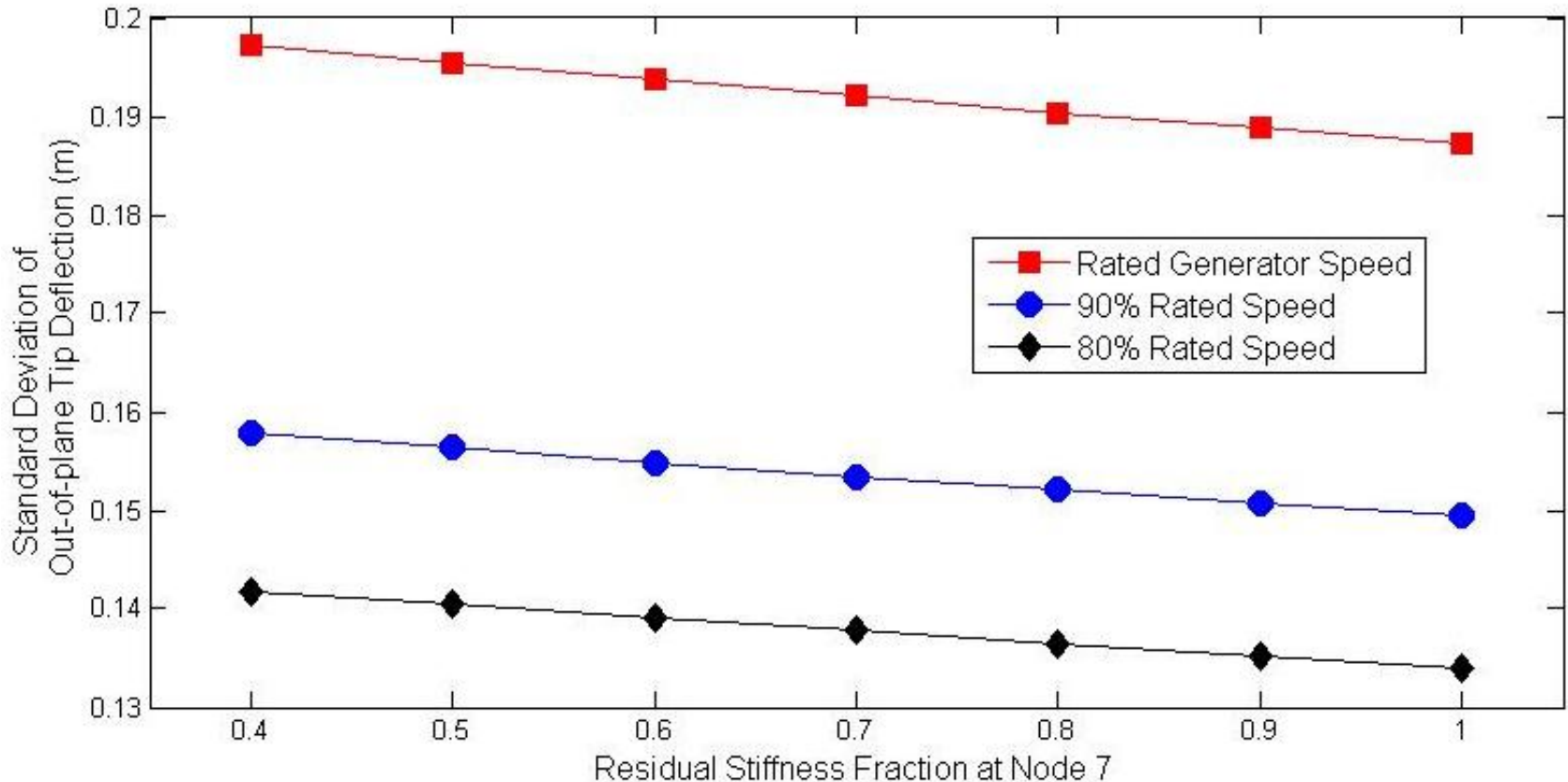


- Pitch & wind speed dominate change in stiffness
- Damage detection tool needs to factor out impact of pitch and wind speed to use deflection



Change in Tip Deflection with Power Output

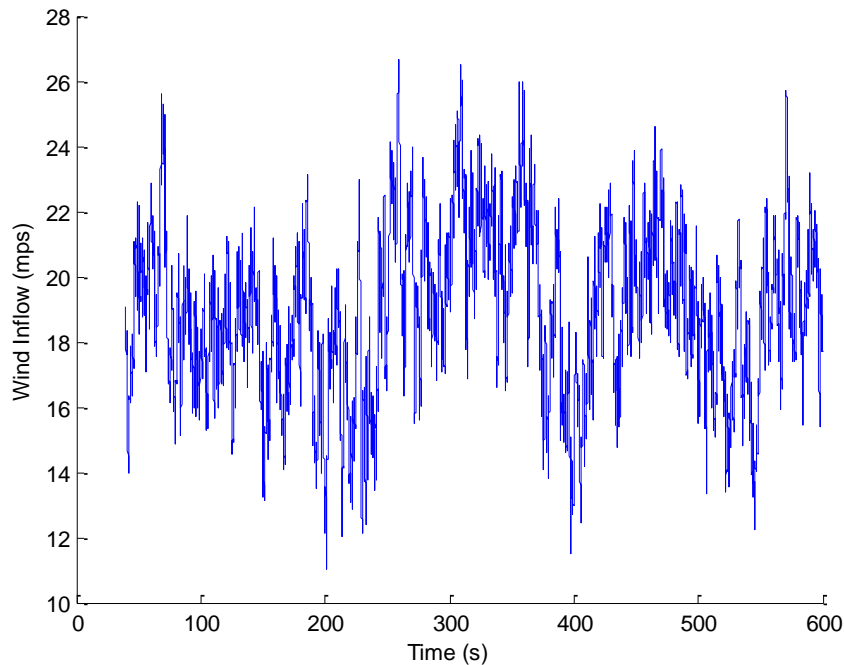
Hypothesis: Reducing power output through generator set-point reduction will reduce loads on turbine blades



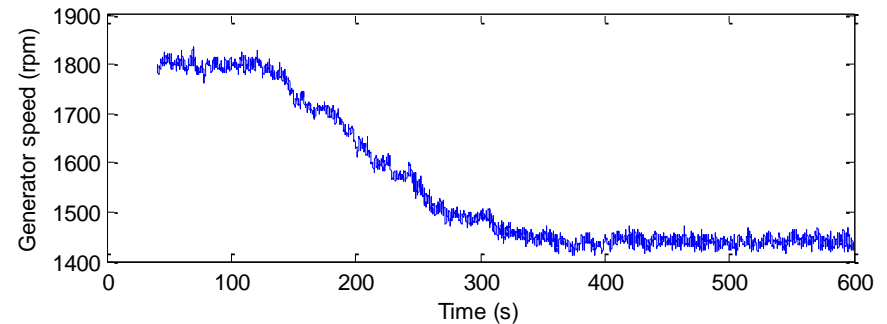
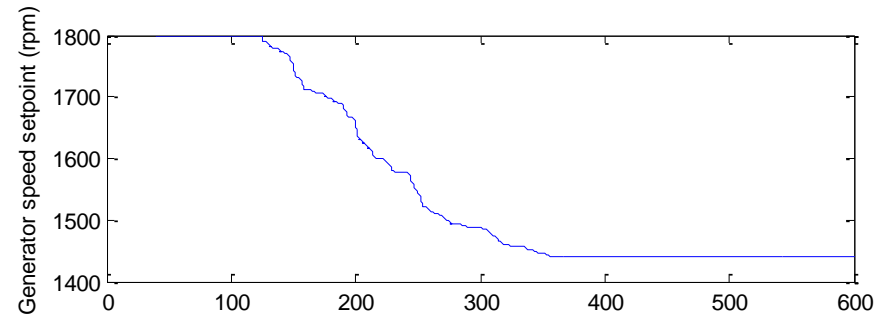
Out-of-plane tip deflection std. dev. for 3 generator set-points & 7 damage levels.



De-rating Generator for Reduced Loads



Simulation Wind Input



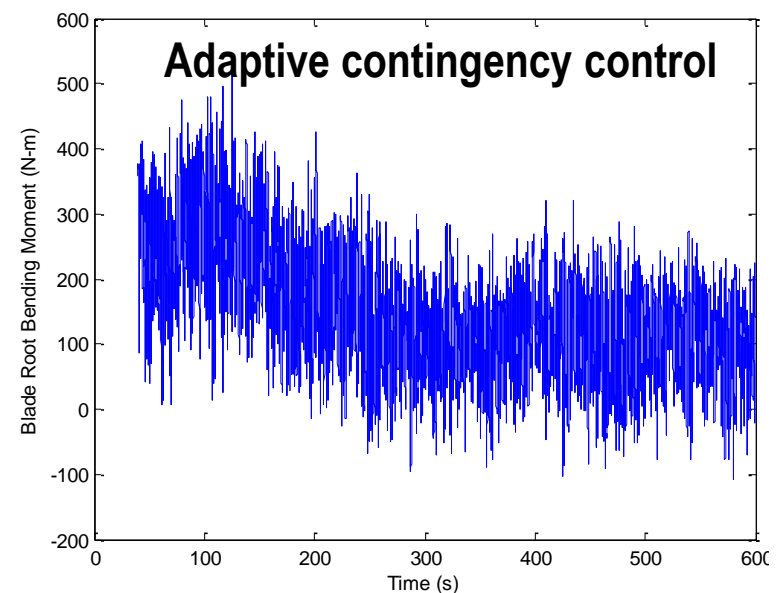
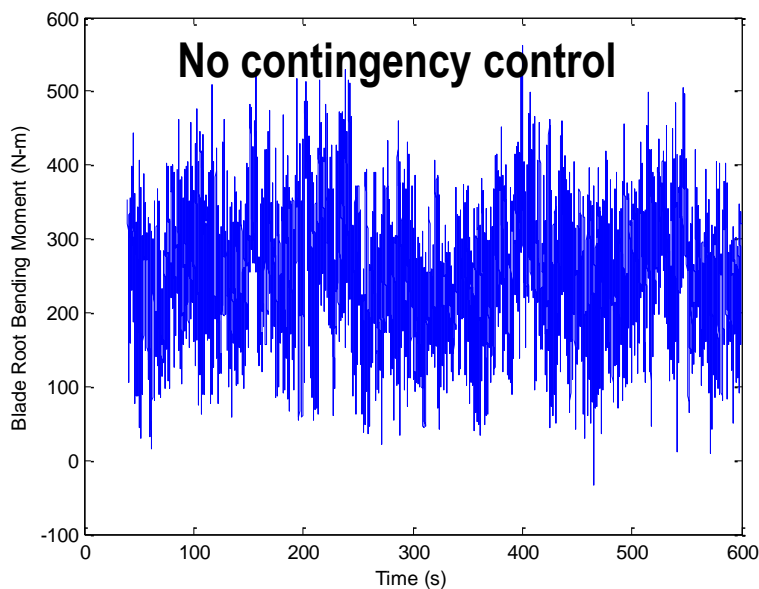
Top: Generator set-point
Bottom: Generator speed



Control Integrated with Condition Monitoring

- Simulation demonstrating contingency controller lowering generator set-point for turbine with blade damage when winds are turbulent & above rated speed
- Resulting decrease in blade root bending could extend service life

Blade root bending moment





Thanks to My Collaborators

Khanh Trinh, PhD

SGT

NASA Ames Research Center
Moffett Field, CA

Brian Taylor, John Burken

NASA Dryden Flight Research Center

Edwards AFB, CA

Mark Balas, PhD

University of Wyoming

Laramie, WY

Alan Wright, PhD

NREL

Golden, CO

Marc Bodson, PhD

University of Utah

Salt Lake City, UT